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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF METHODS FOR IMPROVING THE OPERATING CHARACTERISTICS OF CABLES WITH CROSS-LİNKED POLYETHYLENE INSULATION

Speciality: 3306.01 – Electrotechnics, electrical engineering

Field of science: Technical sciences

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GENERAL CHARACTERISTICS OF THE WORK

Relevance and the study and the degree of elaboration. The unique electrophysical and chemical properties of polymers make them widely applicable as the main insulating material in power engineering, particularly in the insulation systems of medium-, high-, and extra-high-voltage cables. The quality and durability of energy systems directly depend on the performance of these materials. However, during operation, factors such as electric fields, elevated temperatures, and mechanical stresses cause significant changes in their properties. A comprehensive study of these effects is therefore essential to ensure the long-term and stable performance of insulation systems.

Cross-linked polyethylene (XLPE) is the most widely used material in polymer-insulated cables. Nevertheless, operational experience has shown that such cables often fail earlier than expected. Theoretical and experimental studies attribute this primarily to the presence of heterogeneous regions in the insulation system. Understanding the mechanisms of their formation and evaluating their impact on insulation performance thus remain pressing issues. Despite extensive research, a unified and unambiguous concept in this area has not yet been established. Considering the limited experimental data available in our country on the production and operation of such cables, the relevance and practical significance of this dissertation increase further.

The decline in quality due to electrical, thermal, and mechanical stresses during the operation of XLPE cables necessitates comprehensive investigations aimed at improving their properties. In particular, the mechanisms of partial discharges, water treeing, and electrical treeing, as well as their influence on the aging and dielectric properties of insulation, were studied in detail.

The dissertation also examines the properties of various XLPE modifications, including peroxide- and silane-based composites, along with processes occurring in heterogeneous regions and their impact on cable service life. Furthermore, an injection-based rejuvenation method was proposed to mitigate defects arising during operation and to extend the lifespan of aged cables. The results demonstrate that effective control of electrophysical and chemical processes significantly enhances the performance and reliability of XLPE-insulated cables.

This dissertation represents one of the first systematic, multidisciplinary studies in our country dedicated to improving the durability and longevity of XLPE-insulated cables. Its theoretical and practical contributions provide a valuable foundation for advancing cable technology and ensuring the stability of power systems.

Object and subject of the research. Various types of polyethylene-based cable composites and insulation materials, medium and high voltage cables. These insulation materials are considered the main material for medium and high voltage cables worldwide to this day. The subject of the research is methods, tools and algorithms for improving the operational characteristics and quality indicators of polyethylene-insulated cables.

Research aims and objectives. The main goal of the dissertation is to develop methods for improving the operational characteristics and quality indicators of cables with polyethylene insulation. For this purpose, the properties of XLPE insulation cables and the materials used were studied and the factors affecting the reliable operation of cables were studied. To achieve this goal, the following main tasks were set:

➢ Scientific and practical justification and analysis of the impact of different, heterogeneous areas of high risk of formation in the insulation system of medium and high voltage XLPE insulated cables at different stages on the cable aging process.

➢ Study of the mechanism of formation and development kinetics of gas voids, which are by-products in polymer composites during the linking process, development of an algorithm for estimating critical dimensions, and study and development of the mechanism of formation of electrical discharges in a gas void confined to a polymer medium and the method for forming the optical effect of individual microdischarges.

➢ Study of the morphology of water trees, the distribution of current density in their branches, and the relationship of these structures to local field distortions, which arise and develop due to the combined effect of moisture and electric field.

➢ Study of the effect of voltage increase level on dielectric strength in samples of various sizes made of cross-linked polyethylene insulation and development of a new method taking into account the non-uniformity of the change in dielectric strength.

➢ Justification of the selection of multifactor criteria for the effect of the aging process on the dielectric properties of XLPE insulated material and development of a method for analyzing, studying and calculating the frequency and temperature characteristics of the cross-linked polyethylene composite over a wide range of dielectric parameters.

➢ Investigation of the effect of electrophysical processes occurring in XLPE composites as a result of temperature fluctuations on the partial discharge parameters and morphological stability of materials, and scientific substantiation of the relationship between thermal aging, partial discharge, and structural changes.

Research methods. The most modern methods were used to study the dielectric properties of the research objects in a wide range, including: Omicron CP100/CPTD1, Omicron MPD 600 for the study of partial discharges, and Perkin Elmer – Spectrum 100, X'Pert PRO, Perkin Elmer Lambda 35, Zeiss EVO LS 10 for the analysis of structural changes, as well as MATLAB/Simulink and Comsol Multiphysics simulation programs for the modeling and study of electrophysical processes occurring in defects in cable insulation, and at the same time, a model was developed for the implementation of injection technology in Solidworks software.

Key points presented for defense:

➢ The possibility and mechanisms of heterogeneous region formation in the polymer insulation of cables at various stages were investigated, along with their impact on the cable aging process

➢ The mechanism and kinetics of gas void formation in cable insulation during manufacturing were investigated. This included the calculation and evaluation of their critical dimensions under various conditions, the mechanism of electric discharge initiation within gas voids confined by polymer medium, and the optical effects resulting from individual microdischarges. These phenomena were studied using the MATLAB/Simulink program.

- Electrical phenomena occurring in gas voids located at different regions within the insulation layer were analyzed. An algorithm was developed to model electric field distortions and current density distributions in water tree structures of varying sizes, evolving over time due to the combined influence of moisture and electric fields. Additionally, a methodology for analyzing electric fields in cable joints—considered sensitive parts of the cable line—was developed using the Comsol Multiphysics® program.
- The electrical strength of single-layer and multilayer sandwich-structured XLPE-based thin samples was investigated. The effect of increasing voltage levels on electrical strength was evaluated, and the electrical breakdown experiment was modeled in the COMSOL Multiphysics® program, taking into account various material inhomogeneities.
- The effect of thermal aging on the dielectric properties of various types of XLPE insulation materials was investigated, and the frequency and temperature-dependent dispersion of XLPE samples across a wide range was determined.
- A comparative study of partial discharge parameters before and after aging in various types of XLPE-based samples was conducted, and the effect of thermal aging on structural changes in cable insulation was examined.

Scientific Innovation of the Research. Taking into account the subject of the dissertation work, the scientific novelty of the research conducted in the direction of developing methods for improving the operational characteristics of cross-linked polyethylene insulated cables is considered to be the following:

1. Based on the analysis of the finite element method, a model, algorithm and structure of air gaps and water trees in cross-linked polyethylene insulated medium and high voltage cables were developed to comprehensively assess their impact on the aging process and life of the insulation, taking into account the shape and dimensions of air gaps and water trees. Based on the developed model, the current density, electric field intensity and potential distribution in the

branches of air gaps and water trees in the insulation, which cannot be determined experimentally, were determined [2].

2. The sensitive parameters characterizing the aging process of XLPE insulation were systematically studied, and the selection of the tangent of the dielectric loss angle and the level of partial discharges as the main criterion parameters was justified. In particular, the change in tanδ, depending on the frequency of the supply voltage during operation, was proposed as a control monitoring of the aging process [7,14,15].

3. Comparatively, for the first time, electrical strength tests at various voltage levels, thermal aging tests of dielectric parameters, dispersion in a wide frequency and temperature range, partial discharge tests, Fourier transform infrared spectroscopy (FTIR), Ultraviolet-visible spectroscopy (UV/V), X-ray diffraction (XRD), and Scanning Electron Microscope (SEM) analyses were carried out on single-layer and multilayer structures of various modified polyethylene insulated composites used in XLPE insulated cables produced in cable factories of our republic [11,13,14].

Theoretical and Practical Significance of the Research. The results obtained in this dissertation can be used to improve the production process in factories manufacturing XLPE-insulated cables in our country, as well as to enhance the quality indicators and service life of these cables during operation in energy complexes. The findings from the research conducted in this dissertation hold theoretical significance for the scientifically sound assessment of the aging process in non-uniform regions of the insulation system of XLPE-insulated cables.

Approval and Implementation. The results of the dissertation work were presented in the collection of scientific works Veles, based on the materials of the III International Conference Winter Scientific Readings (Kiev, 2018); the Republican Scientific and Technical Conference dedicated to the 100th anniversary of the Azerbaijan Democratic Republic on the topic Establishment of the Educational-Research-Production Mechanism (Baku, 2018); the International Scientific Conference Actual Issues of Applied Physics and Energy dedicated to the 100th anniversary of the Azerbaijan Democratic

Republic (Sumgayit, 2018); the International Scientific and Practical Conference Universities of Azerbaijan and Turkey: Education, Science, Technology (Baku, 2019); the International Scientific-Practical Conference Machine-building and Energy: New Concepts and Technologies (Baku, 2021); the conference Modern Problems and Development Prospects of the Electric Power Industry (Baku, 2022); the VI International Scientific and Practical Conference Energy- and Resource-Saving Technologies: Experience and Prospects (Kyzylorda, 2024), as well as being presented and discussed at scientific seminars at the Azerbaijan Technical University.

Name of the organization where the dissertation was carried out. The dissertation work was carried out at the Department of Electrical Engineering of Azerbaijan Technical University, the High Voltage Laboratory and Central Laboratory of the Faculty of Electrical and Electronics at Yıldız Technical University, Turkey, the Radiation Physics of Polymers and Active Materials Laboratory of the Radiation Problems Institute under the Ministry of Science and Education of Azerbaijan, as well as at the laboratories of the Institute of Physics and the training center of Azerishig OJSC.

Structure and total volume of the dissertation. The dissertation consists of an introduction, four chapters, a conclusion, a list of references, and abbreviations and symbols. The main text of the dissertation, including 62 figures, 26 tables, 37 graphs, and 1 diagram, is presented on 255 pages. A total of 277 sources are cited in the reference list.

The approximate volume of the dissertation’s overall and structural sections, in terms of characters, is distributed as follows: Total – 245,647 characters; Introduction – 22,816 characters; Chapter One – 47,896 characters; Chapter Two – 14,920 characters; Chapter Three – 80,281 characters; Chapter Four – 67,834 characters; Result – 8,204 characters.

SHORT SUMMARY OF THE DISSERTATION

In the introduction, the relevance, practicality, and feasibility of the dissertation topic are determined and justified, based on an extensive analysis of scientific research conducted in this field. The devices and methods used for the experiments are selected in accordance with the nature of the work. The main provisions put forward for defense and the tasks set to achieve the goal are outlined in the introduction. Additionally, the scientific innovations of the dissertation are presented, based on the results of the research conducted on the topic. Furthermore, the pragmatism, validation, and potential applications of the findings from the dissertation are highlighted.

In the first chapter, a literature survey was conducted to identify the factors affecting the quality of installed polyethylene electrical cables, to explore existing problem-solving methods, and to assess the current state of these cables.

First, extensive research was carried out on the factors influencing the quality of polyethylene-insulated power cables and the methods for addressing existing issues. The historical development of cable lines in electric power systems and key technological innovations were reviewed. Special emphasis was placed on the advantages of XLPE-insulated cables. Their widespread use in countries such as the USA, Canada, Germany, Russia, and others highlights their effectiveness. Notably, the mass production and implementation of this type of cable began in Azerbaijan in the 2000s.

According to the survey results, the degradation of XLPE-insulated cables is primarily influenced by electrophysical processes resulting from electrical, thermal, and mechanical stresses. In particular, the formation of electrical and water trees, air voids, and partial discharges within the insulation significantly affects its longevity.

In this context, the properties of polymer materials and their applications in insulation systems were analyzed. It was found that the mechanical properties of insulations made from thermoplastic composites deteriorate at high temperatures, thereby limiting their thermal stability. To address this issue, a polyethylene cross-linking process is employed, resulting in a XLPE material with enhanced thermal and mechanical stability.

Finally, three primary methods for the production of XLPE composites—peroxide, silane, and radiation cross-linking—were compared. The formation of voids during the vulcanization process and their electrophysical effects were examined, with particular attention to the impact of void size on partial discharge intensity. A comprehensive and extensive literature survey was conducted, reviewing recent research studies from developed countries on all these aspects.

In the second chapter, in line with the objectives and scope of the dissertation, the research objects were identified as medium-, high-, and ultra-high-voltage cables, as well as XLPE insulation composites. The research methods, models, and algorithms developed for the analysis of electrophysical processes were described. Samples were prepared using hot pressing, and their dimensions were specified. Electrical strength tests and other necessary experiments were conducted at Yıldız Technical University. The samples were tested using voltage ramp rates of 500 V/s, 2 kV/s, and 3 kV/s. Additionally, measurements were performed on multilayer samples using the same methodology.

The dielectric parameters of the insulating materials were measured after 450 hours of thermal aging, and the results were analyzed across a wide range of frequencies and temperatures. The sequence of measurements is presented in Figure 1. The impact of thermal aging on the insulating materials was thoroughly evaluated. Furthermore, conducting the dielectric analysis over a broad frequency and temperature spectrum enabled a more comprehensive and accurate assessment of the materials' properties.

Figure 1. Schematic representation of the step-by-step procedures followed during the research process

To evaluate the effect of thermal aging on the partial discharge level and morphological properties of XLPE composites, tests were conducted both before and after the aging process. The overall scheme of the study is presented in Figure 2. Partial discharge measurements were carried out using an Omicron MPD 600 device. In parallel, the algorithms and boundary conditions of the models used to simulate the distribution of electric field, potential, and current density were developed. These models replicated real cable conditions with water trees and air gaps of varying sizes and shapes, and were implemented using the COMSOL Multiphysics software.

The third chapter of the dissertation focuses on the primary causes of cable aging, emphasizing the inhomogeneous regions formed within the insulation system and the processes occurring in these areas. It was observed that the electric field concentrated in these regions initiates various electrophysical phenomena at the weak points of the insulation, ultimately leading to premature cable failure. Although several researchers have proposed methods that have reduced the failure rate of XLPE-insulated cables, the mechanisms underlying the formation of inhomogeneous regions and their influence on the insulation aging process have not yet been fully investigated.

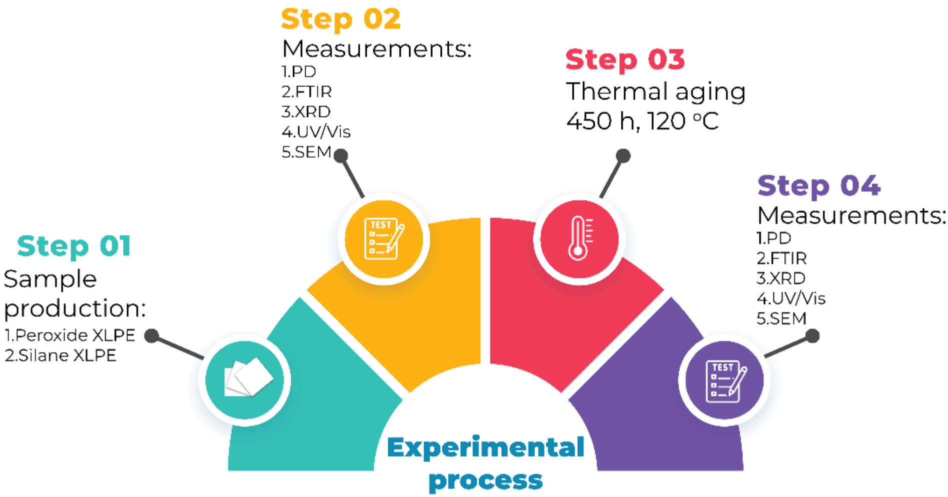


Figure 2. Overview of the experimental procedure.

Furthermore, the analysis of numerous experiments conducted on XLPE-insulated cables over the past 50 years indicates that the operational characteristics and remaining service life of these cables can only be accurately assessed through comprehensive studies. At the same time, investigating the impact of external factors on the cable aging process remains a pressing issue. Therefore, a holistic approach has been applied to address the challenges discussed in this chapter, and a schematic representation of the heterogeneous regions is provided in Figure 3.

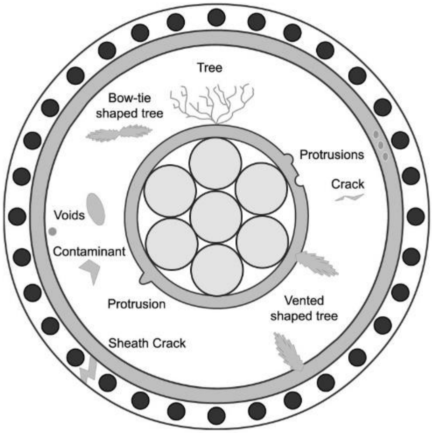


Figure 3. Schematic representation of possible defects in cable insulation

The formation of non-uniform regions in XLPE-insulated cables can be classified into three stages: (1) defects originating during the manufacturing process, which include not only technological flaws but also issues related to material quality and cleanliness; (2) defects introduced during the installation and laying of cable lines; and (3) non-uniformities that develop during the usage time.

The heterogeneous regions formed during these stages impact the reliability, safety, and efficiency of the insulation to varying degrees. Analysis and research findings indicate that one of the primary causes of polymer cable deterioration is the occurrence of partial discharge in air gaps. This process affects the insulation system as a result of manufacturing defects, contamination, and the degradation of the insulation material.

Given that partial discharges are a key factor in reducing the lifespan of insulation, the process was simulated using MATLAB/Simulink software. One of the resulting graphs from the developed block diagram model is shown in Figure 4. The simulation revealed that the amplitude of partial discharges decreases as the size of the defect within the insulation increases, with larger amplitudes observed at smaller defect sizes.

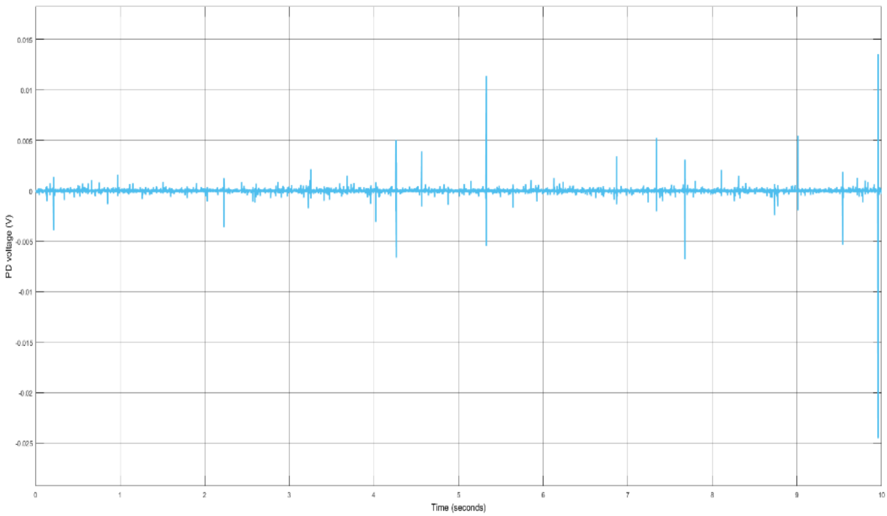


Figure 4. Results of PD modeling for an air gap with index 'd'

As noted, the most common non-uniform regions in XLPE insulation are gas voids and moisture. These regions form both before and during heat treatment. According to the results of the studies, the size, number, area, and nature of the gas voids have a direct impact on the electrical strength of the cable.

In general, the causes of dissolved components in polymer insulation can be categorized into three main groups:

1. Various substances, such as moisture, air, and solvents, may remain in the insulation before thermal treatment.
2. By-products released during the polymerization reaction, decomposition products of organic peroxides, and gases generated from polymer degradation impact the insulation system.
3. Gases that diffuse from the surrounding environment into the polymer during high-pressure heat treatment pose additional challenges.

The peroxide curing process is characterized by the release of methane and acetophenone gases, which form gas voids within the polyethylene at high temperatures. Consequently, ionization occurs in the voids within the insulation, weakening the insulation system and leading to premature failure. These gaseous by-products diffuse into pre-existing air voids with a radius of r_0 in the polymer, causing an increase in their size.

In this dissertation, the kinetics of this important phenomenon have been extensively studied from a theoretical perspective. The size of the voids, as well as the relationship between pressure and modulus, is characterized by the following formula:

$$\frac{P-P_0}{G} = \frac{5}{2} - 2\left(1 - \frac{\alpha_g}{2r_0 G}\right)\lambda^{-1} - \frac{\lambda^{-4}}{2} \qquad (1)$$

Here, P and P_0 represent the internal and external pressures, respectively, G is the elastic modulus of the polymer, and λ is the swelling rate of the void. As shown by this equation, the growth of gas voids is influenced by the physical properties of the polymer and the level of external pressure.

Additionally, the probability of void growth is determined as follows:

$$W = \exp\left(-\frac{Q}{kT}\right) \qquad (2)$$

Here, k is the Boltzmann constant, Q is the energy required for void growth, and T is the temperature. As observed, as the temperature increases, the probability of void growth also increases, thereby reducing the stability of the insulation. Furthermore, the critical radius of a gas void is determined as follows:

$$r_{kr} = \frac{2\alpha_g}{(P-P_0)} \qquad (3)$$

Here, α_g is the surface tension modulus. As indicated by the equation, in order to prevent the void from growing, the external pressure must exceed the pressure of the saturated gases inside the void.

To prevent void growth after the cross-linking process, the cooling must be performed under high pressure. As the temperature decreases, the equilibrium pressure also drops, helping to maintain the stability of the gas voids.

Internal discharge phenomena in the insulating material or at its interface are typically caused by strong and uneven electric fields generated by voids or defects. In this work, in addition to the processes occurring in gas voids, the electrophysical and chemical processes within the trees that contribute to the deterioration of XLPE-insulated cables have been studied in depth. These studies have opened up opportunities to develop proposals for improving the quality of the cables.

Tree discharge is closely related to internal discharge phenomena. Trees begin to form from conductive particles or voids present within the insulation. In this study, the distribution of electric field voltage and potential within the insulation of XLPE-insulated cables with trees of various sizes and shapes was analyzed. The behavior of XLPE-insulated underground cables with different defects was simulated using the finite element method (FEM) in COMSOL Multiphysics software, and a two-dimensional model of the XLPE-insulated cable was developed within the program. The following relevant scenarios were considered:

To determine the effect of different gaps within the insulation on the electric field, a two-dimensional model of a XLPE-insulated cable was first developed and simulated in the COMSOL Multiphysics program (Figures 5 and 6).

• It was observed that the local electric field intensity was higher in an elliptical gap compared to a circular gap (11.5 kV/mm vs. 10.1 kV/mm).

• Additionally, the analysis of gaps with radius of 1 mm and 2 mm showed that the electric field was stronger in smaller-radius gaps (10.1 kV/mm vs. 9.5 kV/mm).

These results indicate that the shape and size of the gap have a direct impact on the uneven distribution of the electric field and the ionization conditions.

To assess the effect of water trees, electrostatic field models were also developed. For this purpose, the field distribution in vented trees of different sizes was analyzed.

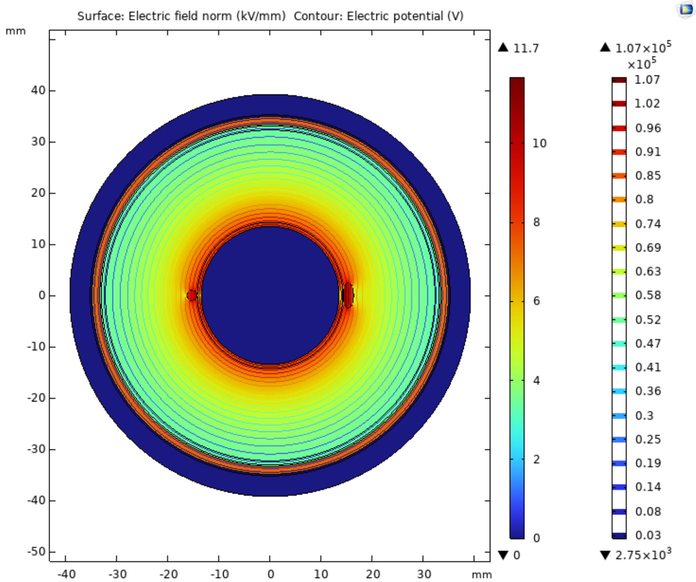


Figure 5. Distribution of the electric field in the presence of gaps with different shapes.

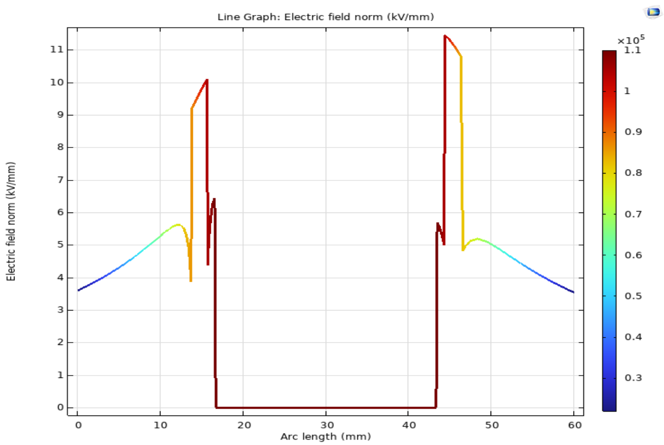


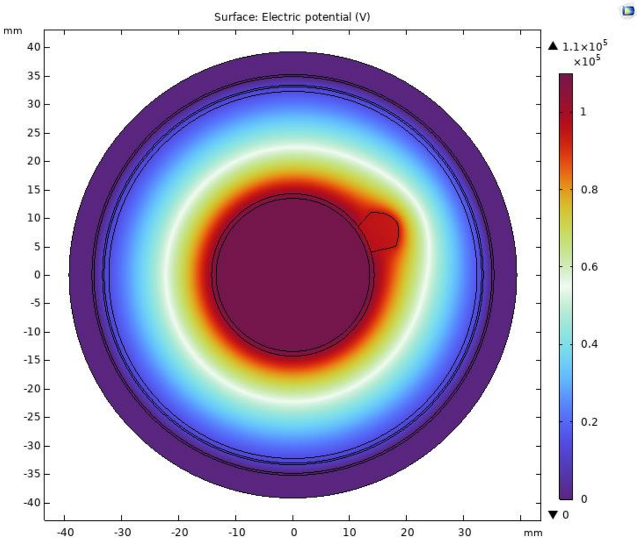
Figure 6. Graph of electric field distribution for gaps of various shapes

The distribution of electric field intensity in two vented water trees of varying sizes, along with their corresponding graphs, are shown in Figure 7.

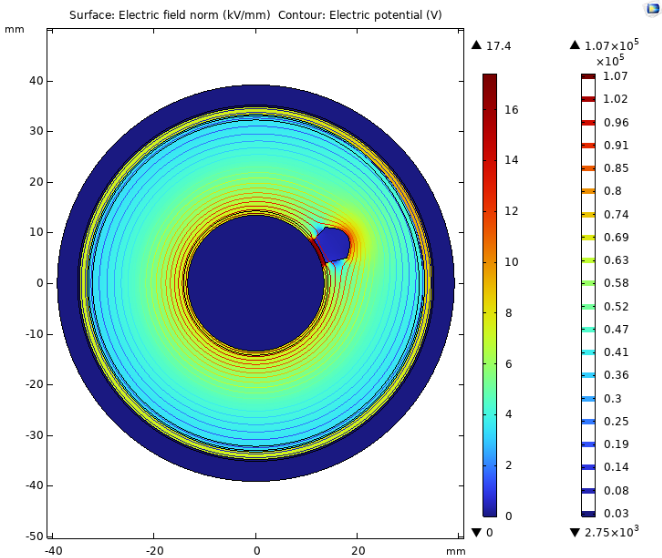
• In the larger tree, the maximum field intensity was 22 kV/mm;

• In the smaller tree, this value was 17 kV/mm.

As a result, these analyses demonstrate that the growth of water trees increases the risk of perforation in the cable insulation and may lead to short circuits between the electrodes. Consequently, voids and trees within the insulation cause an uneven distribution of the electric field, thereby reducing the service life of high-voltage cables. The findings from these research studies enable us to identify the breakdown mechanism of the insulation system in XLPE-insulated power cables and implement preventive measures.



a)



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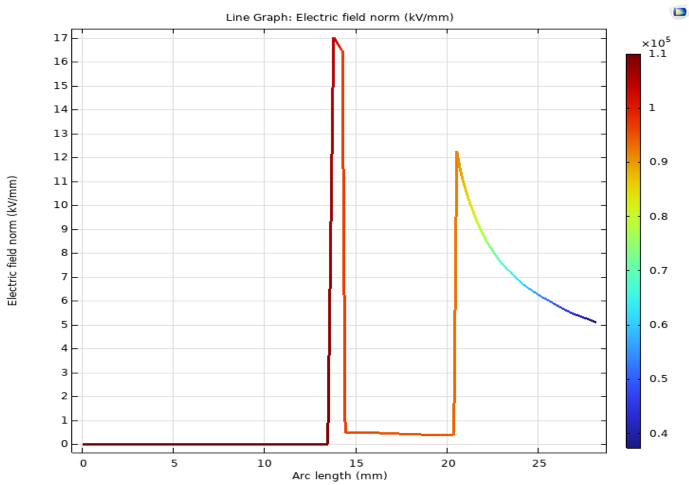


c)

Figure 7. Electric field distribution and corresponding graph curves in a vented water tree: a) electric field; b) potential; c) distribution curves of electric field and potential within the tree

Similarly, the model of a band-shaped water tree and the resulting electric field distribution were also examined in the dissertation.

Water trees typically form in regions with the highest electric field in the presence of moisture, as polar water molecules are directed to these areas under the influence of dielectrophoretic forces. This phenomenon is further supported by the observation of trees in areas close to the cable core.

The calculations in this direction were performed in the region bordering the semiconductor layer to determine the current density in the insulation. To obtain more accurate results, a tree model was developed in three different dimensions. Additionally, considering the nonlinear properties of the insulation, the dependence of specific electrical conductivity on the electric field was also studied. The results of these studies are presented in Figure 8, illustrating the distribution of current density in the tree branches.

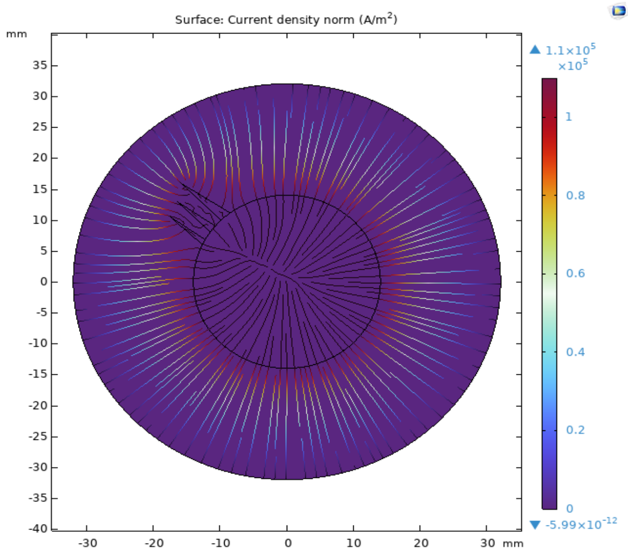
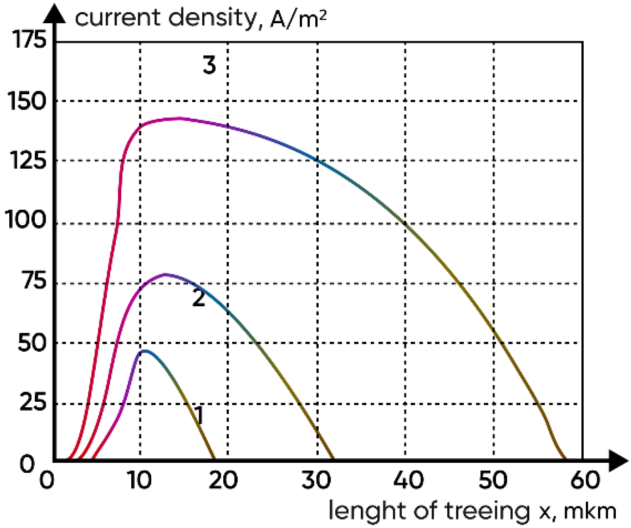


Figure 8. Distribution of current density in the branches of water tree

To study the effect of the length and thickness of the tree, the current density in the branches of a conical 2D tree was analyzed, keeping other tree parameters constant. The graph showing the distribution of current densities in three different tree branches is presented in Figure 1.



Graph 1. Distribution of current density in water trees of varying sizes

According to the obtained results, in water trees, the current flows through the conductive medium. Specifically, changes in the cross-sectional area of the conductive defect at the bottom of the tree branch result in an increase in current density. At the same time, part of the current flows through the moisture channel along the branch, while the other part spreads along the insulation walls, leading to a decrease in current density. Therefore, the maximum current density is observed at the beginning of the tree.

Periodic diagnostic tests are conducted to assess the condition and residual life of cable lines. Based on the results, the frequency of these tests is determined. The condition of cable insulation is evaluated using tanδ and partial discharge measurements, as these parameters are highly sensitive to defects and structural changes within the insulation. In the tests conducted, using criteria adopted from the experience of

Western countries, 48 out of 100 cable lines were rated as serviceable, 14 as partially serviceable, and 38 as unserviceable. These tests were carried out in region No. N in collaboration with the Training Center of Azerishig OJSC. The majority of damaged cable lines were found to date back to the early years of production, installation, and operation of XLPE-insulated cables.

Upon reviewing the condition of the cable system in Azerbaijan, it became evident that defects occurring in the insulation systems of medium, high, and extra-high voltage cables at various stages are the primary factors that degrade their thermal characteristics and shorten their lifespan. One of the most effective methods for addressing these issues is to limit the development of defects and fill the existing gaps with a special solution. This process, known as cable 'rejuvenation,' extends the cable's lifespan by 20 to 30 years through the injection of silicone fluid into the insulation.

The rejuvenation method restores water trees and inhomogeneities in the cable insulation using silicone fluid, thereby enhancing its electrical strength. The composition of the fluid varies depending on the chosen rejuvenation mechanism. During the diffusion process, the fluid penetrates the damaged areas of the insulation, and the method can be applied using either high-pressure or low-pressure techniques. As a result, this process alters the chemistry and physics of the insulation, extending the cable's reliable lifespan. For the application of this method in our country, a special injection head was developed and modeled in Solidworks (Figure 9).

Considering that the operational quality indicators of medium and high-voltage cables with XLPE insulation are largely influenced by the quality of the polymer composites used and the changes in these properties under various factors, **the fourth chapter** of the dissertation presents the results of extensive multifactorial and interrelated research studies on XLPE insulated cable composites.

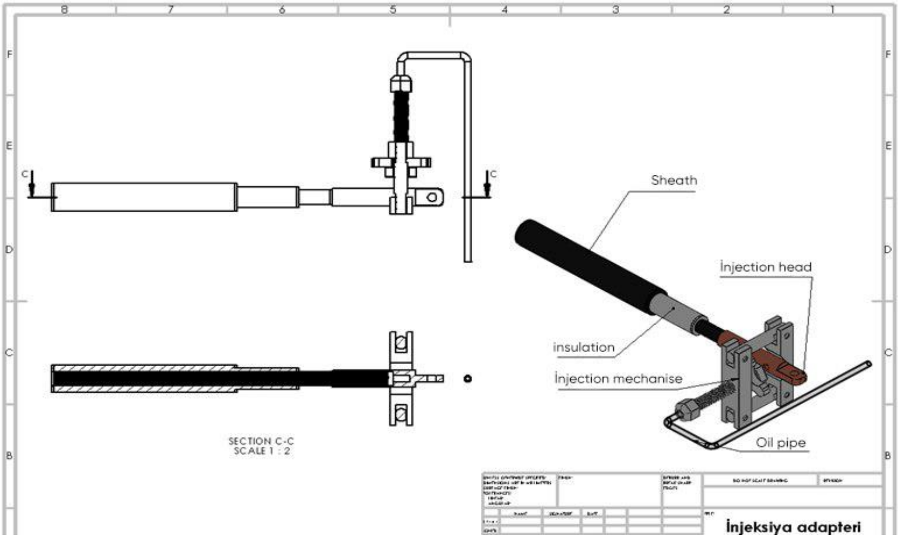
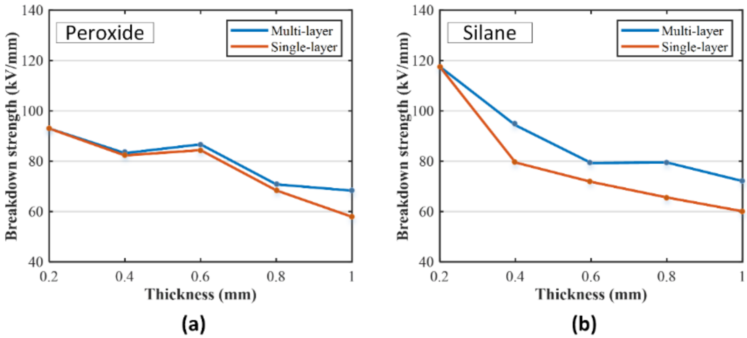


Figure 9. Sketch and design of the injection head

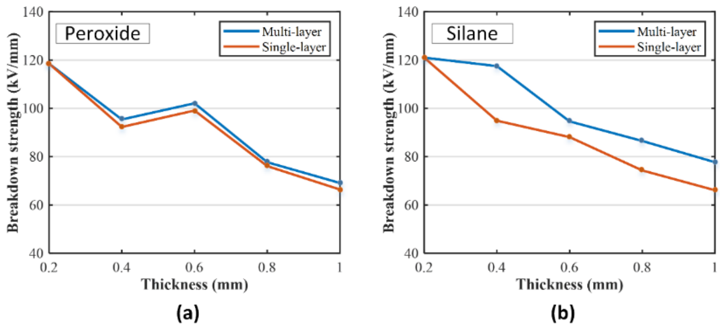
A large-scale literature survey conducted revealed that the number of scientific studies in this area is limited, with most research being one-sided and insufficient for fully revealing the electrophysical and chemical processes occurring within the insulation system. It can be confidently stated that the research studies conducted will help fill certain theoretical and practical gaps in this field. It is also worth noting that the cable composites used in similar cables produced in the cable factories of our country were selected as the object of research. The results obtained are significant as they represent the first comprehensive research on this topic and provide useful and complete material for the cable industry in our country. In addition to measuring the electrical strength of the samples in various configurations, other dielectric parameters, structural changes, and the mechanisms behind these changes were assessed using modern methods, establishing a scientific basis for analyzing and applying the results.

First, the study was conducted using the COMSOL program, and the dielectric strength of both single-layer and multilayer samples was calculated at voltage ramp rates of 500 V/s and 3000 V/s, in accordance with the IEC 60243-1 standard (Figures 2 and 3). The results showed that the dielectric properties of layered structures were superior. Additionally, it was observed that the simulation results aligned with field studies, which enhances the reliability of the obtained results (Figure 4).

In the dissertation, the effect of thermal aging on the properties of the samples was also investigated. The dielectric properties (ε', ε'' and tanδ) of three different XLPE insulation materials were examined under 450 hours of thermal aging across various voltage and frequency ranges.

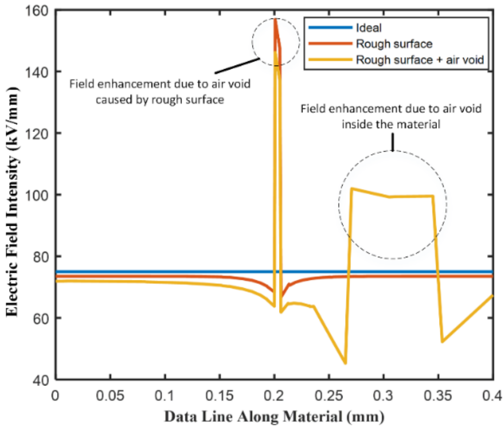


Graph 2. Dependence of dielectric strength on insulation thickness and number of layers at 500 V/s: (a) peroxide, (b) silane



Graph 3. Dependence of dielectric strength on insulation thickness and number of layers at 3000 V/s: (a) peroxide, (b) silane

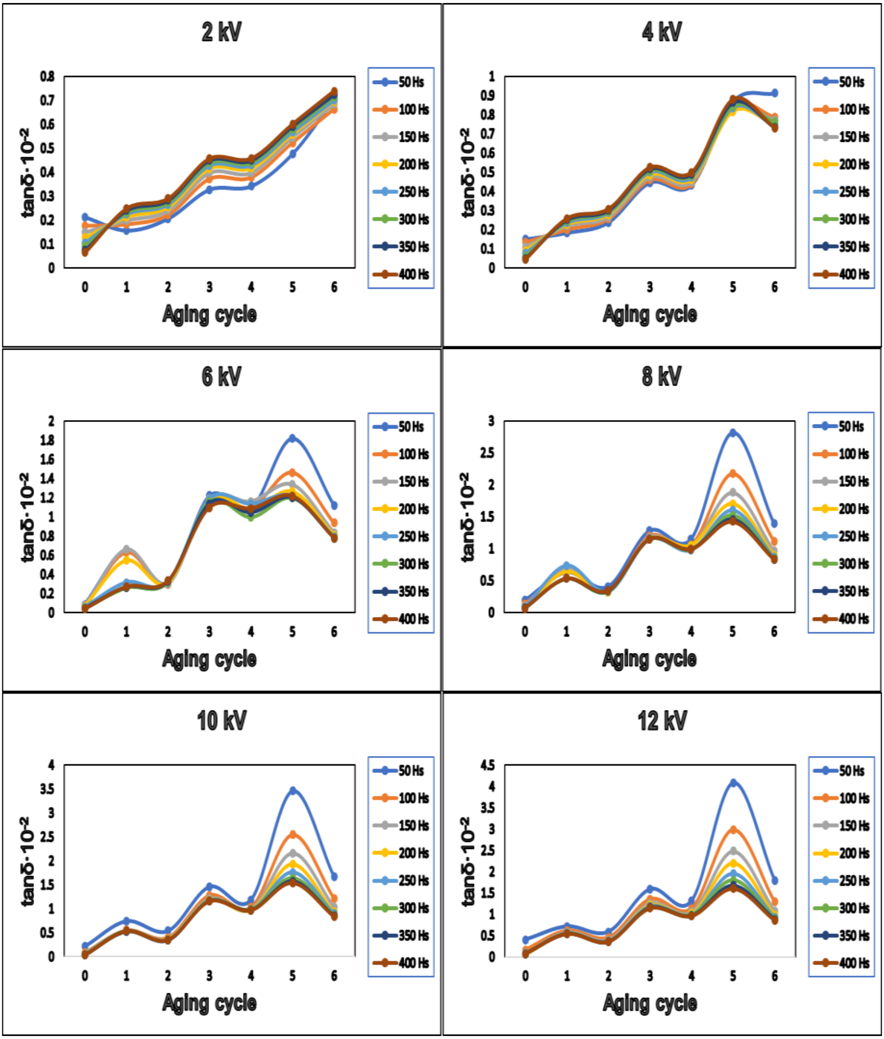
The experiments revealed that as thermal aging progressed, the dielectric loss angle and dielectric losses increased. However, due to the non-polar molecular structure of the materials, no significant changes were observed in the dielectric permittivity. Graph 5 shows the dependence curves of the dielectric loss angle on the aging period for one of the material samples.



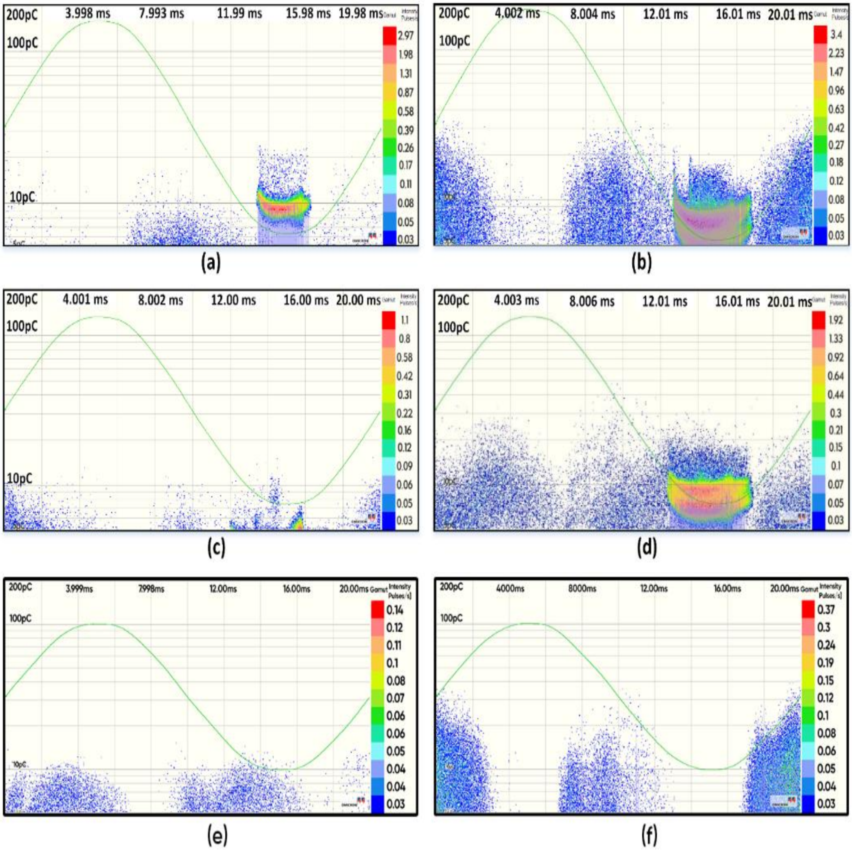
Graph 4. Variation of electric field intensity for ideal, rough surface, and void cases

In addition to studying the effect of aging on insulation samples under various conditions, and recognizing the importance of dielectric parameters as key indicators of insulation quality, the dielectric properties (ε', ε", and tanδ) of two different insulation materials—peroxide and silane-added XLPE insulation composites—were examined over frequencies ranging from 25 Hz to 1 MHz and temperatures from 20°C to 120°C.

The dissertation also investigated the effect of electrical discharges on insulating materials. PD measurements, a key non-destructive method for assessing insulation condition, were used to study the impact of PDs on three different materials and to examine the change in PD levels due to thermal aging (Graph 6). The results revealed that the PD onset voltage decreases as thermal aging increases, with a more pronounced decrease observed in peroxide-containing samples.



Graph 5. Dependence of tanδ for a peroxide-crosslinked polyethylene sample on aging time at different voltages and frequencies.



Graph 6. PD properties of peroxide XLPE: (a) before aging, (b) after aging; silane XLPE: (c) before aging, (d) after aging; light-resistant XLPE: (e) before aging, (f) after aging.

In order to study the structural changes of the tested composite samples after thermal aging, tests were conducted using various modern methods and techniques:

- Fourier Transform Infrared Spectroscopy (FTIR) (Figure 7);
- X-ray Diffraction (XRD) (Figure 8);
- Ultraviolet-Visible Spectroscopy (UV/V) (Figure 9);
- Scanning Electron Microscope (SEM) (Figure 9).

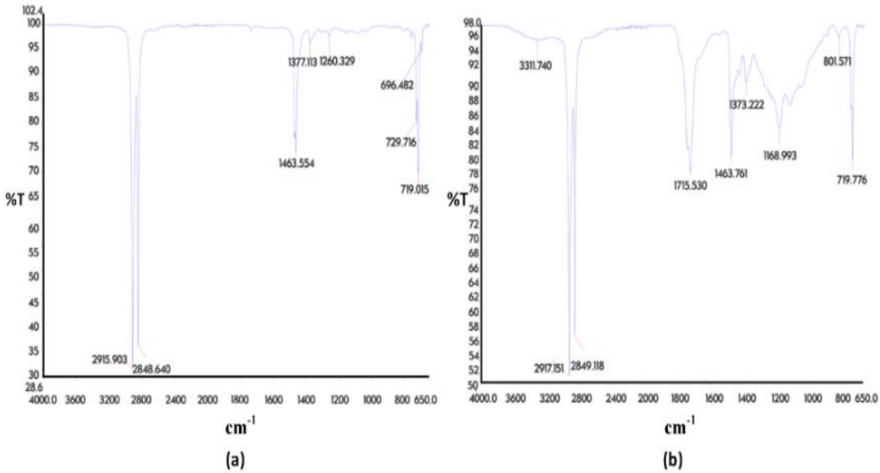


Figure 7. FTIR spectrum of samples: (a) peroxide-containing CLPE – before aging; (b) peroxide-containing XLPE – after aging.

FTIR was used to evaluate the structural changes of polyethylene materials. FTIR analysis was performed on both unaged and aged samples. The measurement results revealed asymmetric and symmetric stretching vibrations of CH2 groups at 2915 cm^{-1} and 2848 cm^{-1}, symmetric deformation of the CH3 methyl group at 1377 cm^{-1}, and absorption of carboxylic acids and ketones at 1715 cm^{-1}. Absorption due to vibrations of the -C-O-C- bond was observed at 1168 cm^{-1}. Changes in the FTIR spectrum indicate that thermal aging causes the formation of hydroxyl and carbonyl groups in the insulation.

In the aged samples, the absorption in the 1000-1400 cm^{-1} region broadens, indicating the formation of C-C bonds in the polymer. In the silane-treated XLPE sample, an increase in the absorption of the -OH function of hydroxyl groups was observed in the 3000-3500 cm^{-1} region.

The changes in the crystal structure of XLPE materials were analyzed using X-ray diffraction (XRD). The XRD results indicate that while thermal aging does not introduce new phases into the crystal structure of the material, it does impact the crystallinity morphology.

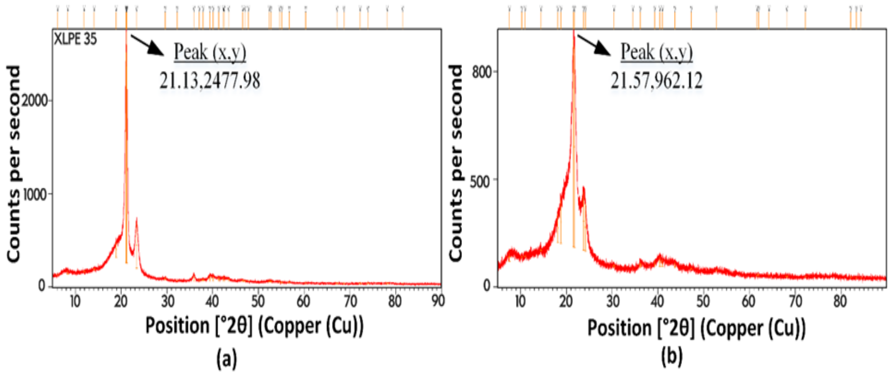


Figure 8. XRD spectrum of peroxide XLPE (a) before aging (b) after aging

The optical band gap energy levels were calculated using the Tauc equation. After the aging process, the band gap energy in the peroxide-containing XLPE samples decreased from 3.91 eV to 3.80 eV. In the silane-containing XLPE samples, this value decreased from 3.40 eV to 3.36 eV.

SEM analysis shows that during the aging process, inhomogeneous areas and irregularities form on the surface of insulating materials. These changes negatively affect the electrical properties of the insulation, leading to a reduction in its lifespan.

In the aging process analysis, a strong relationship between partial discharge (PD) and tangent delta (tanδ) was confirmed by the Pearson correlation coefficient (r). The correlation coefficients for the analyzed peroxide, silane, and photoresist XLPE for covered conductor samples were 0.7734, 0.7895, and 0.7779, respectively. These results indicate that as tanδ increased, PD also tended to increase. Additionally, since the P-value was less than 0.05, this relationship was statistically significant. The T-test results further confirmed the rejection of the null hypothesis, indicating a positive relationship between the two parameters.

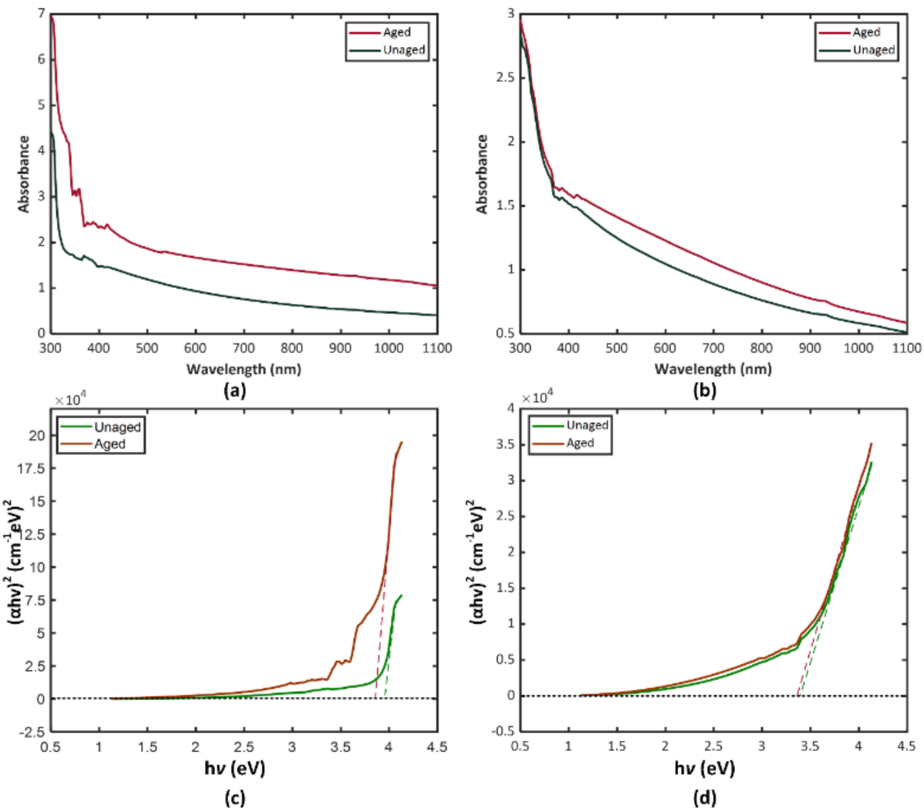


Figure 9. UV/V plots: (a) Absorption spectra of peroxide-doped samples; (b) Absorption spectra of silane-doped samples; (c) Band gap energy of peroxide-doped samples; (d) Band gap energy of silane-doped samples.

The obtained results once again indicate that when assessing the quality indicators of cable insulation, knowing the value of one of the two parameters is sufficient. In other words, by conducting diagnostics based on either of the two parameters during operation, it is possible to assess the current state of the cable insulation system. This approach shortens the time required for cable diagnostics, without compromising the reliability of the results or extending the testing period.

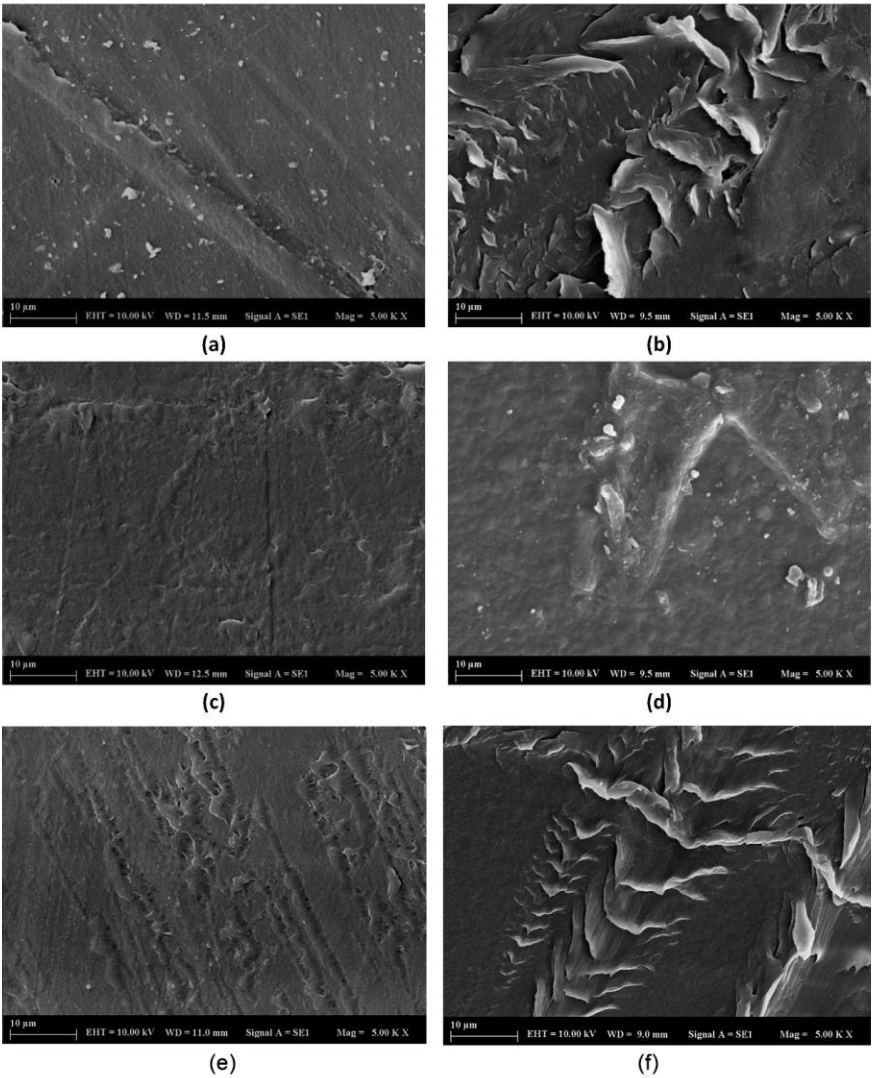


Figure 9. SEM images of peroxide-treated XLPE: (a) before aging, (b) after aging; silane-treated XLPE: (c) before aging, (d) after aging; photoresist XLPE: (e) before aging, (f) after aging.

MAIN RESULTS OF THE DISSERTATION WORK

1. The stability and reliability of power systems largely depend on the quality of XLPE-insulated cables of various voltage classes. Since the production and use of these cables are widespread in our country, improving their quality is of great importance. However, there is no unified concept regarding the causes of premature failures of XLPE cables. This dissertation comprehensively investigates the electrophysical and chemical processes, aging mechanisms, and factors affecting the quality of medium- and high-voltage XLPE-insulated cables. The results obtained are significant for improving the operational characteristics of cables and for assessing their residual lifetime.

2. It was determined that the main factors accelerating the aging process and deteriorating the operational properties of XLPE-insulated cables are gas voids, water and electrical treeing, as well as other inhomogeneities formed in the insulation during production and operation. Considering this, a mathematical model of the development kinetics of initial microvoids likely to occur in the insulation was developed, and their growth conditions and boundaries were determined. It was shown that the growth of voids depends on pressure differences and the surface tension of the polymer. In particular, voids develop under the conditions $1-\frac{\alpha_g}{2r_0G} > 0$, $\frac{2(P-P_0)}{G} \geq 5$, while they remain stable if $P-P_0 < 2\alpha_g/r_0$.

The probability of growth for microvoids smaller than 10^{-4} m was found to be very low, meaning they are not critical for medium-voltage cables. These findings have direct implications for process control in production and for improving efficiency.

Electrophysical processes in gas voids and their influence on insulation were also analyzed. Since direct measurements are not feasible, electric field and potential distributions were simulated using Comsol Multiphysics. Results showed that the electric field in elliptical voids is stronger than in circular ones (11.5 kV/mm vs. 10.1 kV/mm), and higher for smaller radii (1 mm – 10.1 kV/mm, 2 mm – 9.5 kV/mm). Additionally, partial discharge characteristics for voids of different sizes and shapes were obtained via simulation, which is useful for optimizing cable manufacturing and reducing defects [8].

3. One of the most critical factors causing deterioration in XLPE-insulated medium- and high-voltage cables is water treeing. Localized high electric fields in these regions lead to accelerated insulation degradation. In this dissertation, the formation, growth, and electrophysical–chemical processes of water trees were investigated in detail using Comsol Multiphysics. It was found that the electric field intensity reaches 22 kV/mm in large trees and 17 kV/mm in smaller ones. Current density within tree branches ranges between 45 and 140 A/m^2, causing localized heating. This heating dries out the moisture, leading water treeing to transform into electrical treeing, which rapidly accelerates insulation failure. These results enable the identification of overheated regions in the cable and optimization of the thermal regime. Proper adjustment of rated load current and prevention of partial discharges significantly extend cable lifetime and enhance reliability.

4. More than 50 years of operational experience with XLPE-insulated cables demonstrate that their quality and durability are largely determined by the properties and stability of the insulation materials. In this work, the dielectric strength and other electrical properties of XLPE composites were experimentally studied under various conditions. The dielectric strength of peroxide cross-linked samples with a thickness of 0.2 mm was 95 kV/mm, while that of silane cross-linked samples reached 120 kV/mm. At 1 mm thickness, both samples showed values around 60 kV/mm. The lower performance of peroxide samples is attributed to the presence of more structural defects. These results highlight the advantages of the silane cross-linking method.

Furthermore, multilayer structures demonstrated an 18–23% increase in dielectric strength compared to single-layer samples. Simulations confirmed high agreement with experimental data, verifying the reliability of the results. The use of multilayer structures is thus considered an effective method to enhance dielectric strength and improve the operational characteristics of cables.

By increasing dielectric strength, both the reliability and service life of XLPE-insulated cables are improved, while also laying a foundation for optimizing production processes. These findings contribute to strengthening quality control in cable manufacturing and ensuring the stability of power systems [11].

5. Temperature plays a crucial role in medium- and high-voltage cables with XLPE insulation, as excessive heating accelerates thermal aging and shortens cable lifetime. Therefore, the thermal resistance of peroxide-, silane-, and light-resistant XLPE composites was investigated. The dielectric loss tangent (tanδ) was identified as the most sensitive parameter to thermal effects, with maximum values of 0.041, 0.025, and 0.022, respectively, while the dielectric permittivity remained almost unchanged. As aging time increased, the rise in tanδ values reflected the degree of material degradation. Over a wide frequency and temperature range, tanδ maxima of 0.045 were observed for peroxide samples and two distinct maxima (0.005 and 0.011) for silane samples. With increasing temperature, the dielectric permittivity decreased to 2.2. These results confirm that tanδ and related dielectric parameters can serve as reliable indicators of material quality, aging rate, hidden defects, and equipment reliability, ensuring the safe and long-term operation of electrical installations [7,12,13,15].

6. To assess the operational state of medium- and high-voltage XLPE-insulated cables, studying the relationship between aging and partial discharge (PD) intensity is essential. Experience shows that with increased aging, PD intensity rises by about 70%, correlating with growth in the dielectric loss tangent (tanδ). Thus, PD and tanδ measurements are among the most effective diagnostic methods for cables. Tests conducted in the Baku power grid confirmed these findings. Pearson correlation analysis revealed a strong relationship between PD and tanδ, with coefficients in the range of 0.77–0.79. This demonstrates that by measuring one parameter, the other can be accurately estimated, enabling reliable assessment of cable insulation condition [14].

7. Insulation defects in medium-, high-, and extra-high-voltage cables reduce operational reliability and shorten service life. One of

the most effective solutions is the “cable rejuvenation” technology, which involves injecting silicone fluid into the insulation to fill voids and suppress treeing, thereby extending cable lifetime by 20–30 years. Its application in Azerbaijan is therefore considered highly advisable for the restoration of aged cables. For this purpose, an injection head enabling the delivery of fluid into the cable for defect repair was designed, sketched, and modeled in SolidWorks [16].

8. Examination of the insulation system of medium- and high-voltage XLPE-insulated cables after thermal aging revealed notable structural changes. Since such changes accelerate material degradation, FTIR, X-ray diffraction, UV/G, and SEM analyses were conducted. FTIR results showed significant broadening in the 1000–1400 cm^{-1} band, attributed to increased C–C bonds. X-ray diffraction measurements indicated decreases in lattice parameters (a, b, and c). Peak intensity analysis showed a drop from 2477.98 → 962.12 in peroxide samples and an increase from 2826.26 → 3117.75 in silane samples, suggesting that peroxide-based XLPE is more vulnerable to thermal aging than silane-based XLPE. UV measurements further confirmed this, showing a band gap reduction from 3.91 → 3.80 eV for peroxide samples and from 3.40 → 3.36 eV for silane samples. These findings indicate that peroxide-based structures are more sensitive to electrophysical degradation processes.

Overall, the theoretical and experimental results obtained in this dissertation can be applied to improve the operational performance of medium- and high-voltage XLPE-insulated cables and to predict their residual lifetime with greater accuracy [14].

List of scientific publications related to the topic of the dissertation

1. Х.С.Алиев, А.О.Оруджев, М. А. Джамалов. Некоторые вопросы старения кабелей с полимерной изоляцией. Збıрник наукових праць “Велес” За материалами IIIмıжнародноï конференцiï “Зимовı науковı читання” 1 частина м.Киïв 31 сiчня 2018.

2. A.O.Orucov H.S.Əliyev, M.Ə.Camalov. Kabel izolyasiyasının köhnəlmə prosesinə qismən boşalmaların təsirinin təhlili. Azərbaycan

Xalq Cümhuriyyətinin 100 illik yubileyinə həsr olunmuş” Təhsil – tədqiqat- istehsalat mexanizminin qurulması” mövzusunda keçirilən Respublika Elmi – texniki konfransı. Azərbaycan Texniki Universiteti 4-5 aprel 2018.

3. A.O.Orucov H.S.Əliyev, M.Ə.Camalov. Tikilmiş polietilen izolyasiyalı kabellərin istismar müddətinin proqnozlaşdırılması və istismar xarakteristikalarının yaxşılaşdırılması üsulları Azərbaycan Xalq Cümhuriyyətinin 100 illik yubileyinə həsr olunmuş “Tətbiqi fizika və energetikanın aktual məsələləri” Beynəlxalq elmi konfransı 24-25 may 2018. Sumqayıt Dövlət Universiteti

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5 . M.A.Jamalov. Frequency dispersion of dielectric properties of cable polymer insulation composites. Machine-building and Energy: New Concepts and Technologies” International Scientific-practical Conference materials, December 2-3, 2021, AzTU, Baku, Azerbaijan.

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7. M.Ə.Camalov .Kabel polimer izolyasiya kompozitlərinin dielektrik xassələrinin tezlik və temperatur dispersiyası AzTU Elmi əsərlər – Ученые записки – Scientific works, №1, 2021 ISSN 1815-1779.

8. A.M.Hashimov A.O.Orujov, M.A.Jamalov. Some theoretical issues of formation and development of gas voids in cross-linked polyethylene insulation. AJP FIZIKA 2022 volume XXVIII № 3, section En.

9. A.M. Həşimov, A.O. Orucov, M.Ə. Camalov. Termal köhnəlmənin tikilmiş politilen izolyasiyasiyanın dielektrik xassələrinə təsiri. “Elektroenergetikanın müasir problemləri və inkişaf perspektivləri” Beynəlxalq elmi-texniki konfransının məruzə materialları. (17-18 noyabr 2022, ADDA, Bakı, Azərbaycan)

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kabellərin xüsusiyyətləri tendensiya və perspektivlər. Energetikanın problemləri, Bakı, 2024, № 3, s. 16-30

The personal contribution of the applicant in co-authored works:

[5,7,16] – were independently carried out by the author.

[1,2,3,4,6,8,9,10,11,12,13,14,15,17] – the applicant was the main co-author in formulating the problem, conducting the research, analyzing the results, and processing the findings.

The defense will be held on 17th October 2025 at 15^{00} at the meeting of the Dissertation council BFD 2.04 of the Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

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